Improving the Ventilation Efficiency of Jet Fans in Longitudinally Ventilated Rectangular Ducts

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ABSTRACT

The performance of a jet fan in a longitudinally ventilated tunnel is significantly reduced by the proximity of wall or ceiling where important shear stress losses occur. The paper focuses on the effect of jet fan inclination on the reduction of these losses; reducing losses means improved installation efficiency manifested by increased ventilation flow for the same fan power input. Experimental tests were carried out on a model at scale $1/5.5^{th}$. They allow one to determine the optimal jet pitch angle and the resulting benefit that could be drawn out of this solution in the case of tunnels with rectangular cross-sections. Also a few separation distances between the fan and the ceiling were investigated.

KEYWORDS

Jet Fan, Tunnel, Ventilation, Model, and Experimental.

INTRODUCTION

Longitudinal ventilation by means of jet fans is a solution that is commonly adopted in tunnels, namely for its simplicity of installation combined with reduced capital and maintenance costs. However, the overall performance of a jet-fan in a longitudinally ventilated duct such as a tunnel is significantly lessened by the proximity of wall or ceiling (Kempf, 1965); Rhone, 1979 ; Rohne, 1985). Yet for obvious reasons such as presence of traffic, jet fans are lined up along the walls or the ceiling of the tunnel. It is assumed that in rock tunnels with high roughness as much as 30 to 40% of the jet fan thrust is lost in extra shear stress due to the high velocity close to the wall. The only manner of reducing these losses is inclining the jet away from this wall. This can be achieved by means of deflection blades (Lotsberg, 1997) at the outlet of the fan.

A different approach would be to pitch the fan by pointing its outlet towards the middle of a downstream cross-section of the tunnel.

Experimental studies show that a slight pitch increases the ventilation efficiency significantly. How important the gain is and how much benefit could be drawn out of this solution, was the start of this study in 1995. Similar investigations of ducted jets have been carried out in other research laboratories (Tabarra, *et al.*, 1994), mainly for tunnels with circular cross-section (Armstrong, *et al.*, 1994).

OBJECTIVE OF THE STUDY

Initially set up to visualize and record the flow structure around a jet fan in a tunnel, this allowed for the opportunity to investigate the influence of inclination and separation from the wall of a jet fan on its ventilation efficiency in a tunnel.

The more specific objective of this paper is to relate the experiments and see how they may agree with results obtained in other laboratories.

EXPERIMENTAL INVESTIGATION

Test Facility

At scale 1 to 5.5, the test rig reproduces a simplified cut-and-cover two lane tunnel with a rectangular cross-section of .92 m wide by 1.52 m high, yielding an hydraulic diameter D_h = 1.14 m. With its length of 12 m it represents a section of a tunnel of about 66 m long. This length of more than 10 tunnel diameters, is commonly accepted as being long enough for the jet plume to have completely decayed. The model is made of wooden panels where floor and ceiling are concerned, and the walls on either side and over their entire length are made of plexiglass panes.

The jet fan is reproduced at the same scale of 1 to 5.5 (see photo 1). The fan has an impeller with three wings and is driven by a pneumatic motor with rotational speeds of over 20,000 rpm. The tip clearance is 1 mm and the fan has a .48 hub to tip ratio. The external length of the fan is 195 mm. In order to make it as realistic as possible, silencers have been simulated, so allowing jets to be produced with an initial diameter of 108 mm. Eject velocities of up to 25 m/s could be achieved.

The jet fan is mounted in the vertical symmetry plane of the tunnel and is located at a distance of 1.74 m from the entrance cross-section of the model. This would ensure that the flow pattern at the level of the inlet of the fan is sufficiently regular. For the same reason, the tunnel is provided with a bell mouth inlet. A system of four screws attaches the fan to the ceiling and allows it to be pitched as well as its separation from the ceiling to be changed.

No external ventilation source was used to create the flow inside the tunnel model.

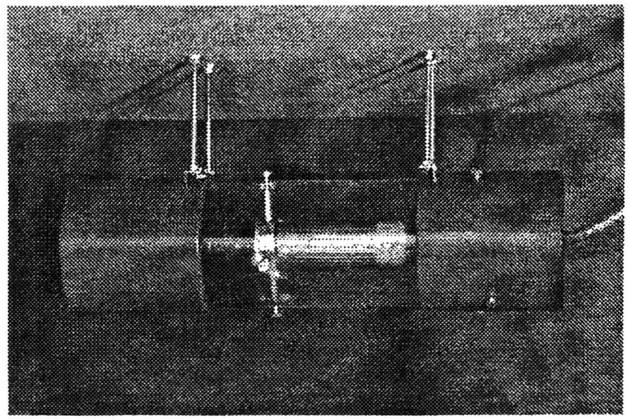

Photo 1. Small scale jet fan.

Measurement Technique

The air flow rates were obtained by applying a 6 by 7 point Log-Tchebycheff integration technique. In order to ensure the most accurate measurements possible, a Doppler laser anemometer was used. It is an Aerometrics, two component based Argon laser (4 W) fitted with a 80 MHz Bragg cell. It is also capable of measuring reverse flows.

The laser optics were mounted on a robot arm which has a two dimensional movement freedom, i.e. horizontal and vertical direction. Since the robot itself is mounted on wheels, the axial direction is obtained by moving it along the facility on a parallel path (see photo 2). The length of the vertical shaft and the horizontal arm allows spans that cover 2 m and 1.9 m respectively. The displacement has a discrimination of .09 mm. Unfortunately, because the focal distance of the optics is .75 m, only half of the width of the tunnel could be explored.

In order to overcome this limitation, the symmetry of the flow pattern needed to be checked beforehand. A flow measurement session by Pitot tube enabled us to verify this aspect. As can be seen in figure 1, the flow pattern determined in a cross-section at 10 m downstream distance from the entrance, is fairly well symmetric with respect to the vertical plane.

Unfortunately, it happens to be less symmetric with respect to the horizontal plane. No explanation can be given despite the fact that the jet fan was lined up with a laser beam.

Despite this fact, what is of interest to this study is that measurement points limited to the half cross-section (with respect to the vertical symmetry plane) could be relied on.

Seeding of the flow was achieved by spraying a heated polycyclic alcohol. Each point of the Tchebycheff integration matrix was measured at least twice and their average value retained as the resulting measurement.

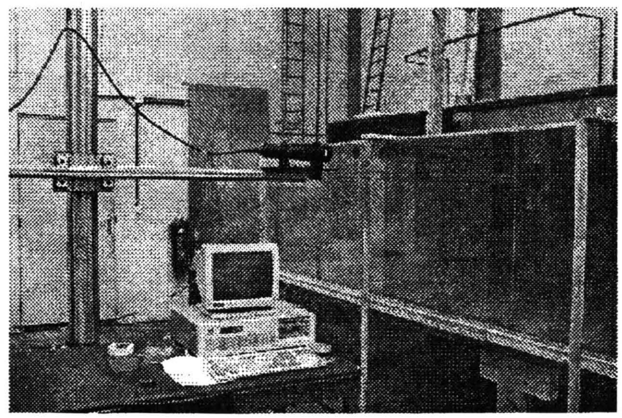

Photo 2. Test facility.

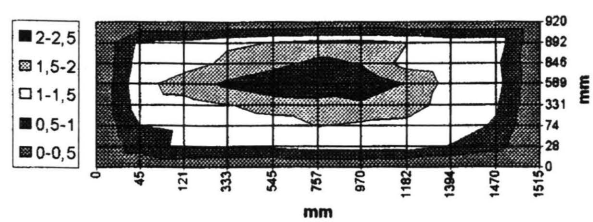

Figure 1. Cross-sectional velocity pattern.

INSTALLATION EFFICIENCY

Dimensioning the ventilation in tunnels with jet fans usually makes use of the 1-D free jet model for which the concepts of continuity and conservation of momentum (Jacques, 1991) apply.

Unfortunately, this model does not account for phenomena such as the Coanda effect and the very important shear stress losses that occur at the walls. These losses are always in excess of the ones assessed by the simple longitudinal friction losses due to the bulk air flow with velocity v_T.

Since the frictional and other opposing forces on the tunnel flow must be balanced by the rate of change of momentum, the ventilation efficiency of a system with jet fans is normally defined as the ratio of work W_T that needs to overcome these forces to the energy W_{JF} supplied by the fans. The efficiency is thus defined as :

$$\eta = \frac{W_T}{W_{JF}} .$$

Where bulk air flow volumes that have a rather regular velocity profile in a duct are concerned, the well known 1-D model can assess the energy sink in a reasonably well manner by the formula :

$$W_T = \frac{(p_{out} - p_{in})}{\rho_T} + \frac{v_{out}^2 - v_{in}^2}{2} + g(z_{out} - z_{in}) + (\lambda \frac{L}{D_h} + \sum_i \xi_i) \frac{v_T^2}{2}$$

However, where the energy source is concerned, i.e. jet fans, the Rankine-Froude model derived from a free jet in co-flowing stream :

$$W_{JF} = \frac{\rho_{JF}}{\rho_T} v_{JF}^2 (1 - \frac{v_T}{v_{JF}}) \frac{A_{JF}}{A_T}$$

yields less satisfactory results.

Assuming that the work W_T is correct and stays constant, values of the efficiency $\eta < 1$ accounts then for all the losses due to the jet. They could also be interpreted as the comparison between the ideally available thrust of the fan and this thrust value that effectively contributed to the ventilation. In this case, the efficiency accounts for a series of effects, of which the most important are :

- Coanda effect,
- nature of the jet whether annular or plane,
- confinement of the flow,
- inclination of the jet centerline,
- separation from the wall,
- recirculation of entrained flow,
- initial mean velocity of the jet,
- turbulence intensity,
- swirl.

Unfortunately, these effects are also, but not in the least, dependent on the geometry of both fan and tunnel model. Moreover, ducted circular jets are rarely axisymmetric and therefore will often entrain tunnel flow in an asymmetrical manner.

Some simplified configurations and effects can and have been studied in laboratories, but a certain number of unknown quantities are still very difficult to accurately assess, more particularly where losses due to tunnel air flow and jet fans are concerned. In a general manner, as (Armstrong, *et al.*, 1994) have already stated, there is no universal descriptor available for ducted jets. This means that different tunnel configurations or test rigs yield results where efficiency values are concerned that are not directly comparable.

Therefore it would be suggested to express the possible gain as a ratio of the resulting tunnel flow rate that is obtained by changing the pitch angle to the one considered as a reference flow rate with the horizontally positioned jet fan. This ratio is expressed as a coefficient of performance (COP). This coefficient would then be proportional to the square of the ratio η_α / η_0 , where η_α is the efficiency at pitch angle α and η_0 the efficiency corresponding to the jet fan in the horizontal position.

TEST RESULTS

Inclination of Jet Fan

Several inclinations for a given separation distance of $s = 110$ mm were examined. The measurements were taken at a cross-section 11 m distant from the entrance, which corresponds to 8 D_h downstream from the outlet section of the fan. The successive velocity profiles showed that the jet plume had almost decayed over this length. Graphical tools allowed to visualize these data in contour graphs, either in the symmetry plane or in a cross-sectional plane (figure 2 being such an example).

All experiments were carried out with Reynolds numbers of the order of 1.5×10^6.

For each cross-section the velocity profile was determined. However, reproducing these profiles in this paper would be too space consuming. Therefore, only one example of a longitudinal profile has been displayed in figure 2.

The test results for the considered separation distance, i.e. 110 mm, have been gathered in Table 1.

Table 1. Measurement results for several pitch angles.

Inclination	**0°**	**2.5°**	**5°**	**7.5°**	**10°**	**12.5°**
average velocity (m/s)	1.5	1.7	1.6	2.0	1.9	1.9
flow rate (m^3/s)	2.1	2.4	2.2	2.8	2.7	2.6

These results may suggest an optimum for the pitch angle of around 7 ... 8° and a gain in performance of roughly 30 %.

The closest comparable and only available case in literature (Cory, *et al.*, 1997) concerns results obtained with a 1/15th scale model (cross-section .3 m high by .55 m wide) equipped with a jet fan that was simulated by a nozzle with a center body (hub to tip ratio of .5) and guide vanes. For a separation expressed as $2s/(H-d) = .27$ which is similar to our case, the optimum measured pitch angle was also around 8°. However, the COP assessed on their plotted efficiency curves would only yield a value of 1.05, which is surprisingly low. But, it must be emphasized that this coefficient is also a function of the mean jet velocity which is, unfortunately, not mentioned in their paper.

From our investigation, it also appears that the variation of the flow rate is less important for greater angles around the optimum than it is for smaller ones, which is also consistent with other results in the literature.

The evidence of these few values is supported by our visual observation during the test (laser sheet) and an interpretation of the mean velocity profile diagrams. For an angle of 12.5°, there is indeed a tendency for the plume to bend towards the floor (see figure 2). This explains the decreasing installation efficiency with further increase of the pitch angle due to higher shear losses, but this time at the floor. For the low values, one may observe a dead zone underneath the jet fan due to a recirculation phenomenon of the flow. This phenomenon tends to increase with decreasing pitch angles which, of course, does not contribute to the enhancement of the installation efficiency.

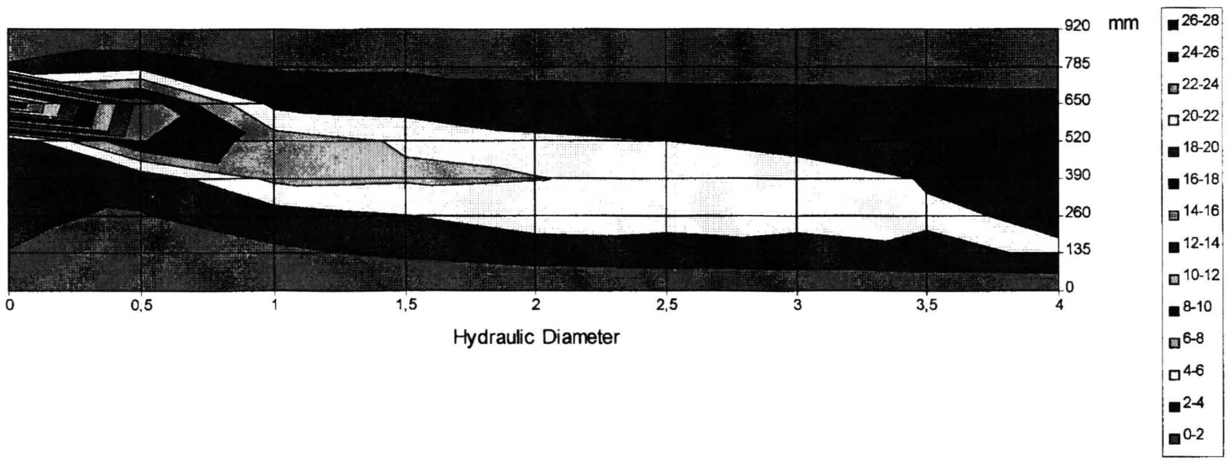

Figure 2. Axial velocity profiles for pitch angle 12.5°.

Separation from Wall

According to (Cory, *et al.*, 1997), a greater horizontal separation would result into an increased installation efficiency, which is quite obvious since maximum efficiency would be expected with a central position of the jet.

On the other hand, (Armstrong *et al.*, 1995) showed that the optimum pitch angle depends on this separation value; in fact greater separation values correspond to lower pitch angles of the jet fan.

Therefore, it was also interesting to verify this conclusion in the case of our rectangular cross-section. The experiments were conducted for two more realistic values of the separation in view of finding out whether the tunnel flow rate would be sensitive to these changes. The values chosen were 80 and 95 mm respectively, so covering a range from .7 to 1 d. Making the assumption that the optimum pitch angle would not go over 10°, each test series was organized for four inclinations of the jet fan, i.e. 0° which is considered to be the reference, 5°, 7.5° and 10°. Indeed, the mean velocity profiles showed that for more important inclinations, the velocity would become too high at floor level (road surface) which would lead to the opposite effect, i.e. increasing the wall shear losses at the floor, which in turn would entail a lower installation efficiency. Besides, from a mere tunnel user's point of view, it would be unacceptable to have high air velocities at the level of the traffic.

The results are brought together in Figure 3.

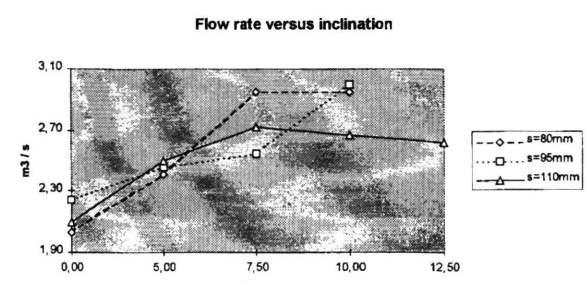

Figure 3. Tunnel flow rate as a function of pitch angle.

Interpretation of the curves allows one to conclude that in the three cases pitch angles of around or more than 7° are suitable and be close to the optimum value, despite the fact that the curve "s=95mm" shows a probably aberrant point at $\alpha = 7.5°$ (unfortunately this particular experiment couldn't be repeated). The COP values are 1.28 for the configuration with $s = 80$ mm, 1.34 for the one with $s = 95$ mm, and 1.30 for the one with $s = 110$ mm respectively.

However, these few results do not allow one to determine whatever relationship exists between pitch angle variations and separation. Within our rather small range of practical values, one may conclude that there is no evidence that the installation efficiency would be sensitive to the separation from the ceiling.

DISCUSSION AND CONCLUSION

This paper is far from an exhaustive study, but may contribute to the understanding of the physical mechanism that underlies the behavior of a confined jet.

Unfortunately, until now there has been no universal descriptor available that would be capable of providing information concerning the ideal location and inclination of a jet fan given the geometry of tunnel and the specific characteristics of the fans.

This study has to be considered as one more experimental contribution to the description of the very complex behavior of a ducted jet fan: it provides a lot of data that could be used to validate CFD models.

The outcome of this study for the more particular case of rectangular cross-sections and separation values ranging from .7 to 1 *d*, would suggest that the best inclination angle of a jet fan lies around 7 ... 8°. These angle values are in agreement with results obtained at other research laboratories. Although the COP value of 1.34 in the case "s=95mm" could be disputed, fact is that the three cases show measurable gains. They may suggest that higher tunnel flow rates of around 25 ... 30 % more could be expected.

NOTATION LIST

A	cross-sectional area
d	jet diameter
D_h	hydraulic diameter
g	gravity constant
H	height
L	length
p	pressure
s	separation
v	velocity
z	altitude
W	energy per unit mass
α	pitch angle
λ	friction coefficient
η	efficiency
ρ	density
ξ	loss coefficient

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